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SOUND MEASUREMENTS OF THE MOD-2
WIND TURBINE GENERATOR

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ERRATA

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Pages 9 and 10 of the report should be removed and replaced with the attached revised pages.

All of the changes are on page 10 and involve the terms of the equation and their definitions.

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SOUND MEASUREMENTS OF THE MOD-2 WIND TURBINE GENERATOR

by

H. H. Hubbard, K. P. Shepherd, F. W. Grosveld

INTRODUCTION

The development and siting of wind turbines which are acoustically acceptable to the community requires an understanding of the principal sound generating mechanisms, as well as the human response to the associated sounds. To date very few acoustical data are available for large wind turbines (Refs. 1-8) upon which to develop prediction methods and criteria.

The purpose of this paper is to report the results of a systematic experimental study of the sound generated by the MOD-2 wind turbine under steady state operating conditions and for normal values of power generation, wind velocity and ambient temperature. The characteristic radiation patterns and spectra in this paper illustrate the type of sound input data used in subjective testing for the development of acceptance criteria.

This effort is part of the Department of Energy wind energy program which is managed by the NASA Lewis Research Center. The MOD-2 machine was built under contract to NASA by the Boeing Engineering and Construction Co., and the utility selected to participate in the operational portion of the program is the Bonneville Power Administration.

APPARATUS AND METHODS

Description of Site

The wind turbine site at which sound measurements were made is at Goodnoe Hills near Goldendale, WA. (Fig. 1). The installation is on a rounded promontory on the north edge of the Columbia River gorge at a nominal elevation of 884 m (2900 ft). Three MOD-2 wind turbine generators are located on the site as indicated in the inset sketch. The recorded data for this paper were obtained from operations of machine no. 2 (Fig. 2). A limited number of observations from machine no. 1 are also included.

Wind velocity and wind direction data were monitored and recorded continuously from meteorological instruments located near the rotor hub. Likewise temperature and wind gradient data for elevations up to 152 m (500 ft) were recorded from a nearby instrumented meteorological tower. For all data

reported herein the prevailing wind direction was west, the wind velocity range was from 7.6 to 13.4 m/sec (17 to 30 mph), and the temperature range was 7°-18° C. All data were recorded on May 4 & 6, 1981 between 0930 and 1800 hrs.

Description of Wind Turbine

The MOD-2 wind turbine has a two bladed 91.4 m (300 ft) diameter rotor mounted on a 61 m (200 ft) high, 3 m (10 ft) diameter (circular) cross section tower (Fig. 2). It is an upwind machine with a max power rating of 2.5 MW and an operational range of wind velocities from 6.7 to 19.7 m/sec (15 to 44 mph). The outer 14 m (46 ft) section of each blade is movable in pitch angle and is adjusted by a hydraulic control system. Precise rotational speed control is maintained to provide an rpm of 17.5. Blades are tapered in chord from 1.43 m (4.7 ft) at the tip section (NACA 23012 airfoil) to 4.3 m (14.1 ft) at the root (NACA 23028 airfoil). Rotor blades have a built-in twist of 8 degrees, a total area of 197 m^2(2120 ft^2) and a tip speed of 83.8 m/sec (275 ft/sec) (Ref. 9).

A computer control system is provided to monitor the wind velocity and direction, to bring the machine on line when the wind velocity exceeds a minimum value, to determine the optimum blade angle setting during normal operations, and to take the machine off line when the wind velocity falls below the minimum or when it exceeds the maximum allowable value.

Sound Measurements and Observations

All noise measurements were made with commercially available battery powered instrumentation. One half inch diameter condenser microphones with a useable frequency range 3-20,000 Hz were used with two different tape recording systems. One of the systems included a two channel direct recording machine which provides a useful dynamic range of about 100 dB in the frequency range of 25 Hz to 20,000 Hz. This system provided high dynamic range recordings needed for direct playback in subjective listening tests. The other system included an FM four channel recorder having a useful dynamic range of about 40 dB in the frequency range of 0 Hz to 1,500 Hz. This FM system provided the recordings from which the data of this paper were obtained. For some recordings the microphone signals to both recorders were C-weighted in attempts to more effectively utilize the available dynamic

ranges. Sound pressure level measurements were also taken with a precision sound level meter on the linear scale as well as for weighting networks A and C.

Data were obtained for distances up to about 275 m (900 ft), and at various azimuth angles from 0° (on axis upwind) to 180° (on axis downwind). The measurement locations for both tape recordings and sound level meter readings are shown in Fig. 3.

Sound spectral data were obtained with the aid of conventional one-third-octave band and narrow band analyzers, and by means of a recording oscillograph with high frequency galvanometers.

To minimize the detrimental effects of wind noise polyurethane foam microphone wind screens were used and microphones were placed on the ground surface, where wind velocities were relatively low.

Attempts were made to observe the far field radiation patterns and spectra during routine operations in order to define the extent to which the wind turbine noise is detectable above the background noise upwind, downwind and to the side of the machine.

MEASUREMENT RESULTS AND DISCUSSION

Sound pressure data contained herein were obtained from listening observations, from precision sound level meters, and from FM tape recordings. Data are presented in the form of instantaneous pressure time histories, narrow band spectra, one third octave band frequency spectra and overall linear, C-weighted and A-weighted levels. In addition some observations are summarized to indicate the approximate distances at which the wind turbine noise generator can be detected above the background noise.

Instantaneous Pressure Time Histories

The near field data of Figs. 4 and 5 were obtained as an aid in sound source identification on the blades and to provide a basis for interpreting the data in the far field. The microphone used for the measurements was located in the plane of rotation about 23 m (75 ft) out from the base of the tower, and at ground level. The blade tips passed by at time intervals of 1.72 sec. and were within about 18.3 m (60 ft) of the microphone. The instantaneous pressure time history traces of the figures are arranged to show the character of the noise associated with the passages of the blades for

frequencies up to 1,000 Hz in each of several frequency bands. Note that the recordings of Figs. 4 and 5 were made at different gain settings. Peak sound pressure level scales are therefore included to the left of the time history traces to indicate the relative signal amplitudes.

Fig. 4 shows the time history trace of the sound in the frequency range 3 to 1,000 Hz as obtained with the aid of a real time analyzer and plotter. Indicated in the figure are the approximate times at which each of three blade passages occurred. High frequency noise components seem to be most evident when the blade tips are closest to the microphone. On the other hand low frequency peaks are seen at various times on the record.

Similar time history data for several one-third-octave bands are shown in Fig. 5. Data for the one-third-octave band centered at 800 Hz is shown in Fig. 5(a). For this range of frequencies the signal is clearly amplitude modulated at the blade passage frequency. The sound pressure signal rises out of the background noise to a maximum value and returns in about .75 sec which is equivalent to the time for the blade to traverse about 80° of arc. The same general result is noted for data in the 400 Hz and 200 Hz one-third-octave bands except that the respective signals are not so well defined. It can also be concluded from inspecting records in Figs. 5(a) and 5(b) and other similar data that one blade of the machine generates less sound at these frequencies than does the other blade. The reason for this phenomenon is not known.

Similar data for lower frequency bands [see Figs. 5(d) through 5(f)] are more difficult to interpret. There are some suggestions of a peaking of the pressures near the times of the blade passages but the indications are not very clear, and the apparent correlation noted for the higher frequencies deteriorates progressively as frequency decreases. An additional factor is the wind noise which is stronger at the lower frequencies and makes the interpretation of the lower frequency records more difficult.

A general result of this study is that the sound due to the passage of the blades through the air is mainly broad band in character. No discrete frequency components associated with tower wake interactions of the type noted in Ref. 1 were observed for this machine at any of the test locations of Fig. 3 for which recordings were made.

One-Third-Octave Band Spectra

The broad band spectrum associated with the data of Fig. 4 is shown in Fig. 6. Although measured in the near field of the rotor this spectrum is believed to characterize the sound generated by the blades as they interact with the air during normal operation. It can be seen that there are two broad peaks, one in the range of 20-50 Hz and another in the range of 800-1,300 Hz. Both of these spectral peaks are related to similar observations noted for propellers, helicopter blades and isolated airfoils, and are believed to be predictable based on a knowledge of the geometry and aerodynamic flow conditions of the blades (Refs. 10-20). The low frequency peak is related to the thickness of the airfoil and is believed to arise from the effects of inflow turbulence (Refs. 11 & 12). The high frequency peak is, on the other hand, related to the thickness of the turbulent boundary layer of the airfoil at the trailing edge and is believed to arise from the interactions of the boundary layer and the airfoil trailing edge (Refs. 16-18).

The characteristic shape of the spectrum of Fig. 6 is also observed at all of the field points for which spectral data were obtained. For instance the spectra of Fig. 7 have the same general shape as seen in Fig. 6 but in addition show a decrease in sound pressure levels with increasing distance on the axis upwind of the machine. Details of the spectra at the larger distances are not well defined, particularly at low frequencies because of the presence of background noise.

The spectral data of Fig. 8 are for comparable measurement positions at two different azimuth angles; on the axis of rotation upwind and at 90° to the axis in the plane of rotation. Although some differences are noted at the low frequencies, the high frequency levels and spectrum shapes are consistent. This latter result is also consistent with the observations which indicated that the quality of sound heard was similar in all directions.

Narrow Band Spectra

Magnetic tape recordings for several of the measuring points were analyzed on a narrow band basis (.25 Hz effective band width) to check for the presence of discrete frequency components. The data of Fig. 9 are representative of some of the results. A number of discrete frequency components can be located in the range 20-60 Hz. The main components are at frequencies

of 24, 30, 36 and 42 Hz. The shaft speed of the electrical generator is 30 Hz. The other frequencies are believed to result from gearing and/or other accessories. Discrete frequencies were identified only on recordings taken near the plane of rotation of the rotor. Only the 30 Hz signal was identifiable in any of the far field measurements, however it was not considered significant from detection or annoyance points of view for any operating conditions. At frequencies higher than 100 Hz no discrete frequency components were found at any location.

Directivity Patterns

Data obtained by hand held sound level meters were analyzed to evaluate some of the effects of distance and azimuth angle. Data for linear, C-scale and A-scale networks are given in Figs. 10, 11 and 12 to document the noise radiation patterns of the machine.

Fig. 10 contains data obtained by means of the two precision sound level meters for all of the distance and azimuth angle combinations of Fig. 3. The hatched areas contain the values at all azimuth angles for the linear, C-weighted and A-weighted networks, respectively. Lower levels are seen to be associated with measurements using the C-weighted and A-weighted networks. This result tends to confirm the results of Figs. 6-8 which indicated the presence of significant low frequency spectral components. Because the data points for a wide range of angles seem to group together closely it is concluded that the machine radiates sound in a generally uniform manner in all directions.

Fig. 11 contains a plot of measured A-scale sound pressure levels as a function of distance. Data were obtained both from sound level meter readings and the playback of tape recordings for several different distances on the axis upwind and downwind. It can be seen that the levels fall off in an orderly way with distance. The two dashed curves are drawn through the data points at small distances and their shapes are estimated for larger distances upwind and downwind. The measured A-scale background noise level in the test area is noted on Fig. 11 to indicate the probable limit in distance for aural detection of the machine. The observed limit of detection was 1400 m (4600 ft) in the upwind direction. In the downwind direction on the other hand, the noise was clearly audible at a distance of 2100 m (6900 ft), thus

confirming the existence of an elongation of the radiation pattern in the downwind direction. This elongation is believed due mainly to the refraction effects of the wind rather than to any preferred directional properties of the source.

Based on the data of Fig. 11 plus other measurements and observations the polar diagram plots of Fig. 12 have been constructed. Shown on the figure are estimated A-level contour lines for 65, 55, 45 and 35 dB values. Shown also is the detection limit distance for the southwest quadrant, for which the A-level background noise was about 30 dB. It was generally observed that the west direction (upwind) propagated noise signals were relatively steady in amplitude. On the other hand, in both the south direction (crosswind) and the east direction (downwind) the noise signal had a perceptible amplitude modulation at the blade passage frequency. It has thus been suggested that at the larger distances, the noise may be detectable from only the topmost portion of the rotor disk.

NOISE PREDICTIONS

In order to evaluate the environmental impact of any particular wind turbine generator design, validated methods are needed to predict with confidence the levels and spectra of the radiated sound, and to compare them with subjective criteria. The opportunity was taken to test some of the available prediction methods previously used for propellers, helicopters and isolated airfoils against the measured data for the MOD-2 machine. Information is presented with reference to the prediction of the overall sound pressure levels as well as the anticipated frequency ranges of those sound pressure components associated with the fluctuating lift and boundary layer - trailing edge interactions. It is assumed that fully developed turbulent boundary layers exist on the airfoils and that there are no regions of separated flow. Likewise direct acoustic radiations from the turbulent boundary layers and the turbulent wake are not considered significant.

Fluctuating Lift Components

One of the candidate mechanisms for airfoil generated sound is the phenomenon of fluctuating lift due to the interactions of the inflow turbulence in the atmosphere with the blade leading edge (Refs. 11 and 12). The random vertical and horizontal velocity fluctuations cause effective angle of attack

changes which in turn result in unsteady airfoil loads and associated sound radiation. This is an important component in the sound pressure spectra of propellers in static operation (Ref. 13) and of helicopter rotors in hover (Ref. 14); and experience to date suggests the following relationship for the peak frequency (Ref. 11):

$$f_{p_1} = \frac{SV}{d}$$

where
- S = Strouhal coefficient ($\approx .25$)
- V = Section velocity, m/sec
- d = Wake projected airfoil thickness, $t \cos \alpha + C \sin \alpha$
- t = Airfoil thickness, m
- C = Airfoil chord length, m
- α = Angle of attack, deg

Assuming a linear taper in chord and thickness and an effective radius of 0.75, the calculated value for f_{p_1} = 34 Hz. This value is in general agreement with the low frequency random noise peak of Fig. 6. The value of effective radius used here is arbitrary but the value 0.75 has been found useful by others in blade loading considerations.

For particular configurations where laminar flow conditions exist and where airfoil vortex shedding sound may be significant (Ref. 10), the above relationship is also applicable for computing the peak frequency due to vortex shedding. Vortex generated sound is not expected to be detectable for the high Reynolds numbers ($R_N > 10^6$) and turbulent inflow conditions of these tests.

Boundary Layer - Trailing Edge Interaction Components

Another possible mechanism for generation of noise by an airfoil in motion is the convection of the turbulent boundary layer past the trailing edge of the airfoil (Refs. 10 and 15). This mechanism is best represented by an edge dipole which radiates mainly forward and to the sides. The radiated random noise can be characterized by a broad spectral peak, the value of which is related by the well known Strouhal relationship to the conditions of the flow. Thus the peak frequency

$$f_{p_2} = \frac{SV}{\delta}$$

where: S = Strouhal coefficient ($\sim$0.25)

V = Section velocity, m/sec

δ = Boundary layer thickness, m

In evaluating δ it is sufficient to assume flat plate conditions and calculate the thickness of the turbulent boundary layer for a plate length equal to the chord of the airfoil. Thus, from Ref. 20:

$$\delta = \frac{.37\ C}{R_e^{\ 0.2}}$$

where: C = Chord length of airfoil, m

R_N = Reynolds No. = $\frac{VC}{\nu}$

where ν = Kinematic viscosity = .0000157 m^2/sec (.0001713 ft^2/sec)

In the above calculations it is customary to assume an effective radius of the blade. In the present study, values of C, V and R_N were determined for an assumed effective radius at the tip. Note that a higher value of effective radius is selected in this case than for the inflow turbulence case. The tip value is chosen because these boundary layer related phenomena are believed to be more sensitive to velocity (Ref. 21). The calculated boundary layer thickness of .0224 m (.073 ft) results in a predicted value of 940 Hz for f_{P_2}, which agrees well with the frequency of the second broad band peak in the spectra of Figs. 6-8. There is a suggestion from recent studies such as those of Ref. 12 that an alternate frequency prediction method, making use of detailed information about the structure of the inflow turbulence may also be useful.

Other Components

The main components of the sound from the blades of the MOD-2 machine are identified as those due to inflow turbulence and turbulent boundary layer interactions with the blade trailing edges. There are however a number of other sources (Refs. 10-20) which for certain combinations of geometry and operating conditions could also be important at low tip speeds. These include such phenomena as direct radiation from the aerodynamic wakes of the blades and the turbulent boundary layers on their surfaces, vortex shedding associated with laminar flows, blade wakes due to finite thickness of the trailing edges, separated flows due to localized stalling, and the

interactions of the aerodynamic flow with surface roughness, proturberances, cavities and slots (as between the movable tip section and the rest of the MOD-2 blade). Experimental evidence to date suggests that none of these additional sources are important for the MOD-2 machine in normal operations.

Overall Levels

A summation of the significant broad band noise components has been predicted using an approach proposed for propeller blades in Ref. 22. Basic assumptions are that the rotor can be treated as a dipole source and for far field predictions the source is assumed to be concentrated at the hub. An empirical relationship based on that given in Ref. 22 for a fixed observation point has been modified for wind turbine application by adjusting for distance and directivity effects as follows:

$$SPL = 10 \log_{10} KAV_{0.9}^{6} - 20 \log_{10}(.011X) + 20 \log_{10}\left(\frac{\sin\theta}{.259}\right) \text{ dB}$$

where:

$K = 5.10 \times 10^{-7}$ (based on helicopter rotor data)

A = Total blade area, m^2

$V_{0.9}$ = Velocity at 0.9 radius, m/sec

X = Slant distance from hub to observer, m

θ = Angle of observer from plane of rotation, deg

For large wind turbine applications an effective radius of 0.9 is chosen arbitrarily rather than the value of 0.7 used previously for helicopter rotors and propellers (Ref. 22). The dominant portion of the wind turbine spectrum is more sensitive to section velocity while the dominant portion of the spectrum for helicopter rotors, which operate at higher disk loadings, is more dependent on blade loading fluctuations.

Calculations of the overall broad band noise levels for the MOD-2 wind turbine generator are plotted in Fig. 13 as a function of distance upwind of the machine at ground level for comparison with measurements. Two results can be seen. The predicted and measured values seem to be in excellent agreement except for the close-in stations. This good agreement may be fortuitous because of the necessary assumptions in the calculations and possible wind noise contamination of the measured data. The apparently good agreement for the predicted and measured fall off rate with increasing distance suggests that the machine can be represented adequately as a concentrated dipole source for far field prediction purposes.

CONCLUSIONS

Measurements of sound from the MOD-2 wind turbine generator for a range of wind velocities from 7.6 to 13.4 m/sec (17 to 30 mph) and electrical power outputs in the range 0.9 to 2.0 MW suggest the following:

1. Two broad peaks of random noise are identified in the spectra. These peaks which occur in the 20-50 Hz and 800-1300 Hz ranges are evident in the near and far acoustic fields and in all directions from the machine.
2. By comparison of the present results with published data for helicopter rotors, propellers and isolated airfoils it is apparent that the two broad band noise peaks arise from two different aerodynamic phenomena on the blades. The low frequency peak is related to the fluctuating forces on the airfoils due to the non uniform inflow to the rotor disk. The high frequency peak is related to the interactions of the turbulent boundary layers on the blade surfaces with the airfoil trailing edges.
3. Due to the high frequency peak which is readily observable in all directions, observers conclude that the machine is not very directional as a sound source. Thus the A-weighted noise level countours are roughly circular at distances up to about 1,000 ft.
4. Strong wind effects are evident at the larger observer distances. The sound is detectable at greater distances downwind than upwind. Refraction effects due to wind gradients apparently play a significant role in propagation to distances of several thousand feet.
5. No discrete frequency sound pressure components were identified with the rotor. Those which could be observed in the sound pressure data were below 100 Hz in frequency and are all believed to be associated with the power generation machinery components.
6. Available methods for predicting the broad band spectrum peaks and the rate of decrease of sound pressure levels with distance give good agreement with experiment.

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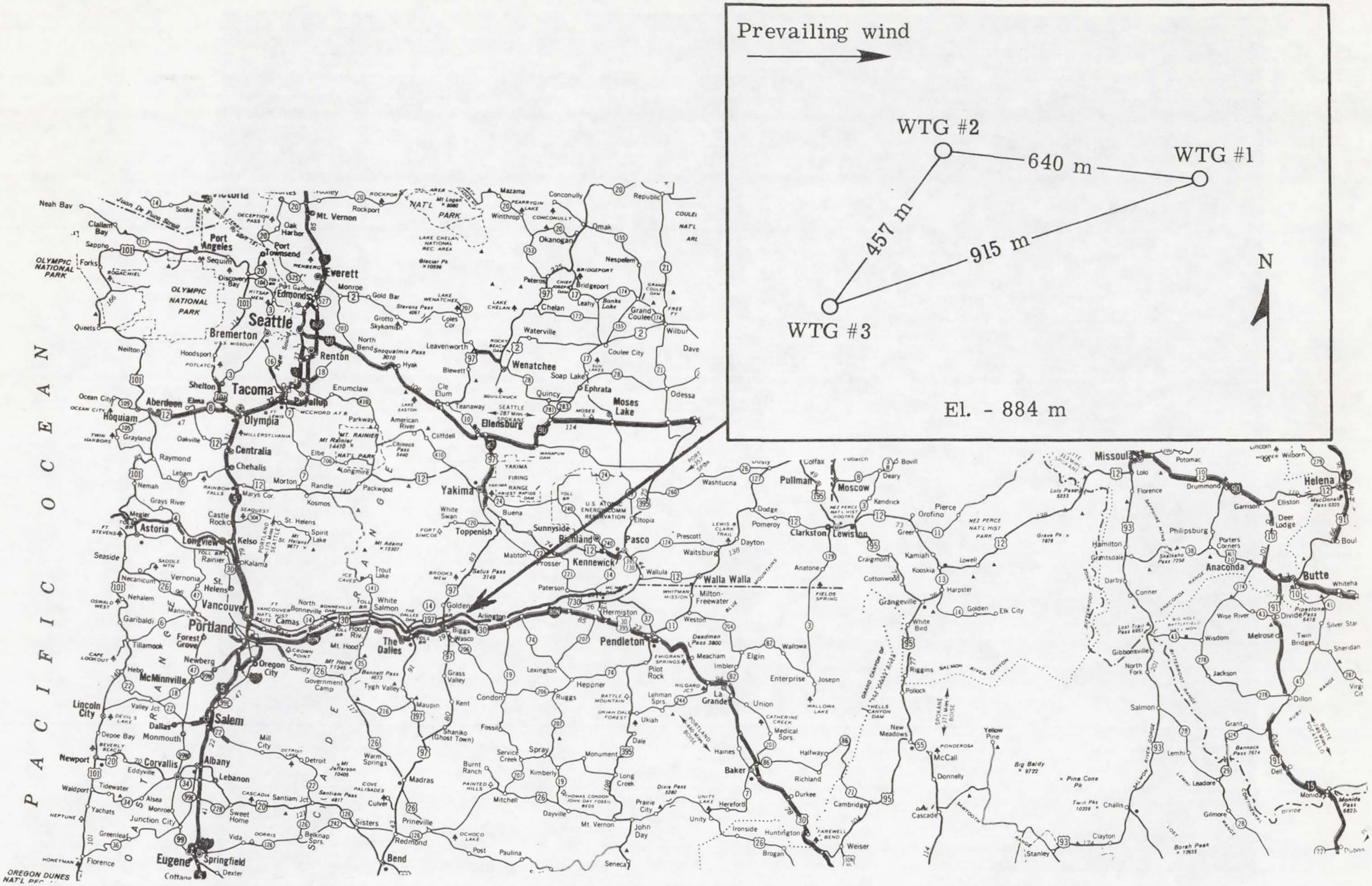


Figure 1. - General Location and Layout of MOD-2 Wind Turbine Generator site.

Figure 2. - Photograph of Wind Turbine Generator #2 in Operation During Acoustic Tests.

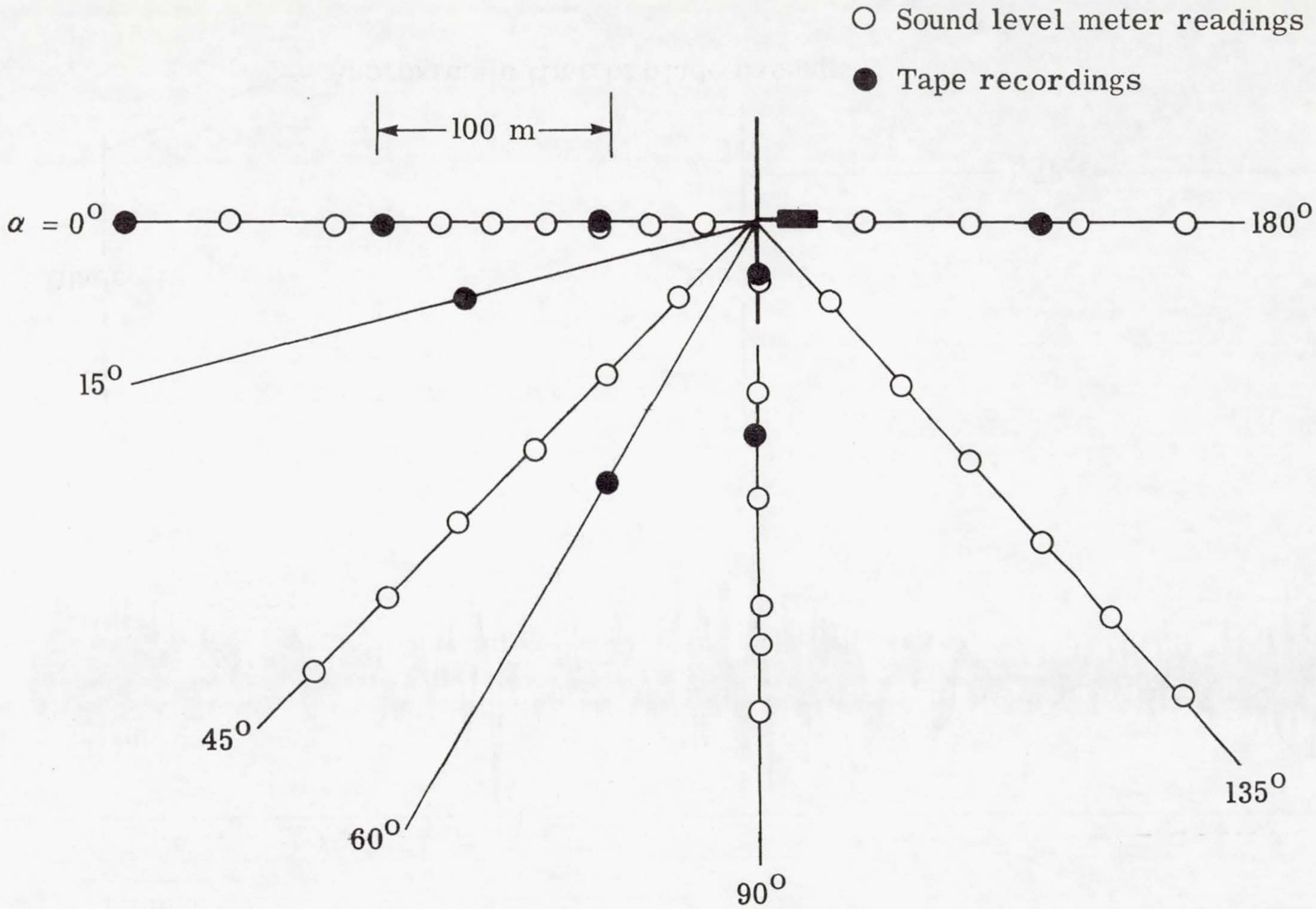


Figure 3. - Plan View Sketch Showing Locations for Which Acoustic Data were Measured for Wind Turbine Generator #2.

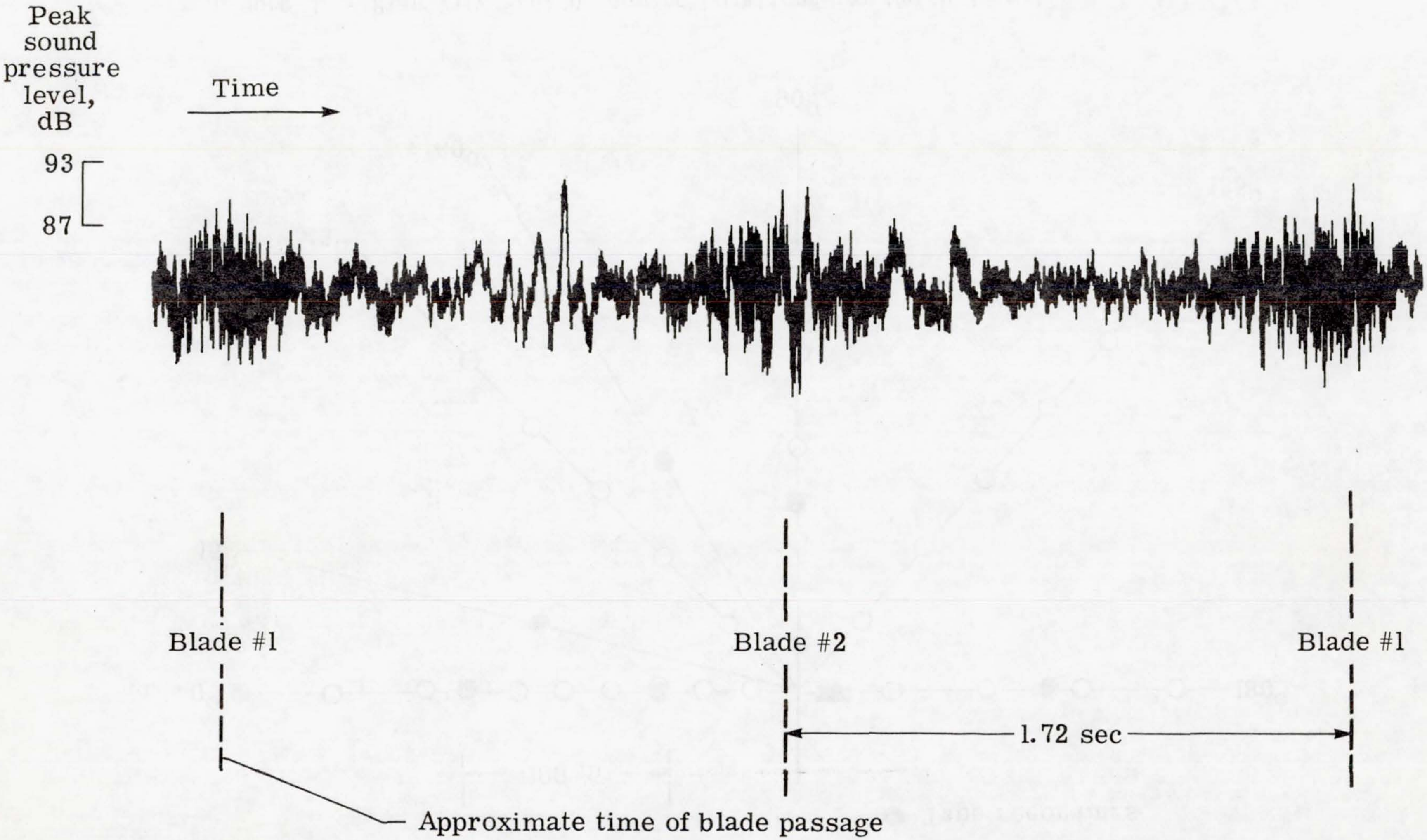


Figure 4. - Time History Trace of the Instantaneous Sound Pressure in The Frequency Range 3-1000 Hz For The MOD-2 Wind Turbine Generator. Data are Recorded 23 m from Base of Tower in Plane of Rotation.

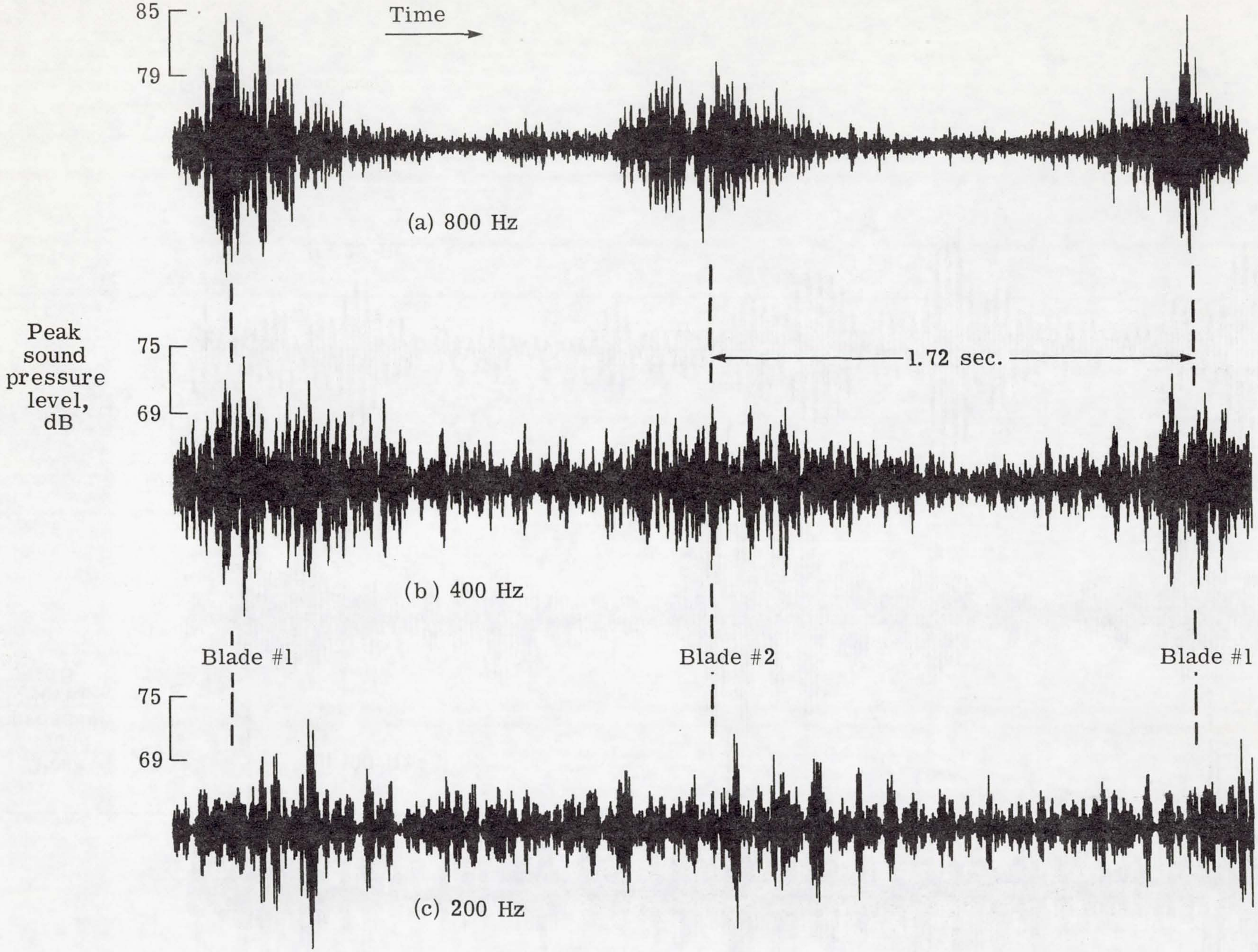


Figure 5. - Time History Traces of the Instantaneous Sound Pressure in Several One-Third Octave Bands Having Center Frequencies from 25 Hz to 800 Hz. Data are Recorded 23 m From Base of Tower in Plane of Rotation. (Cont.)

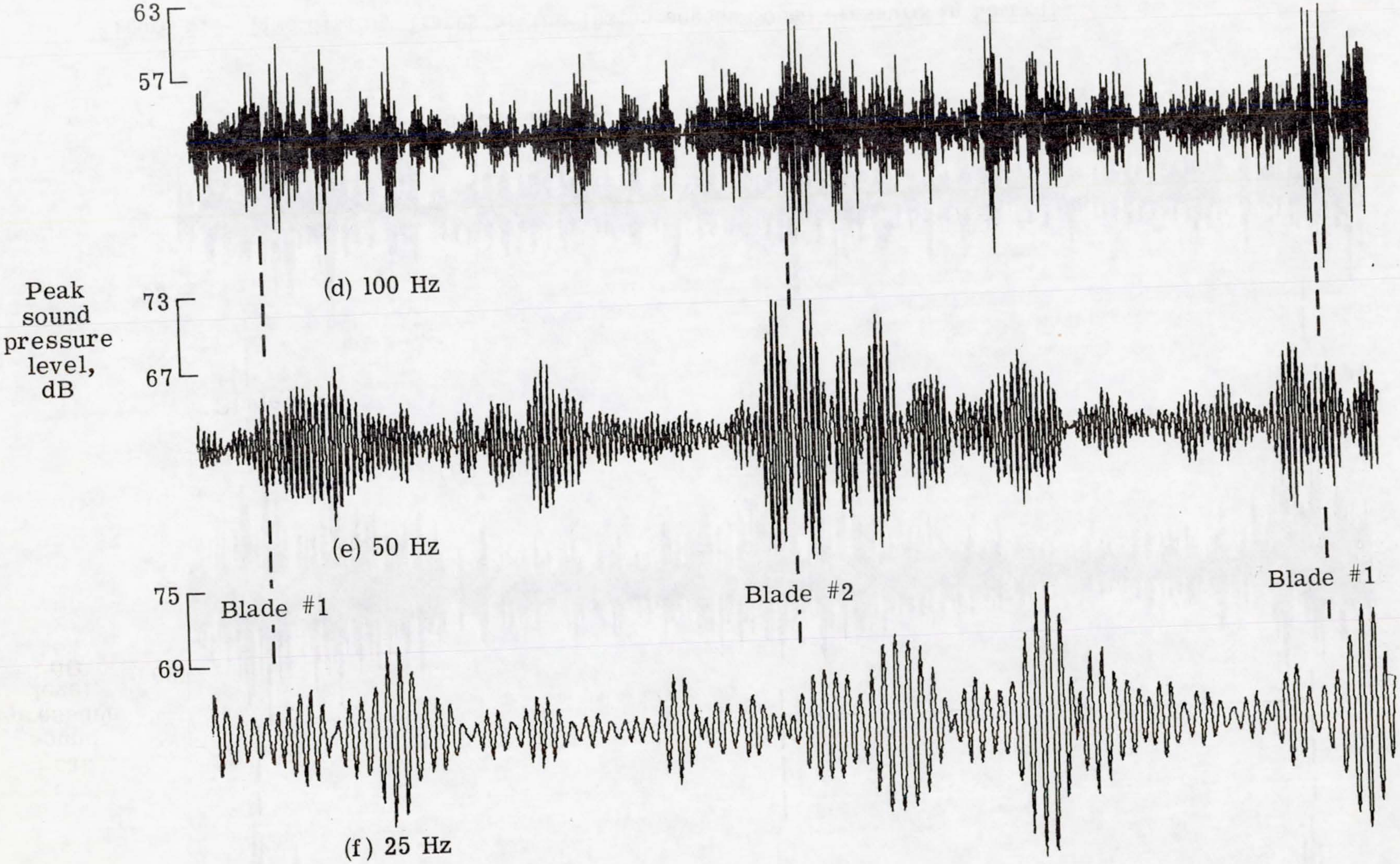


Figure 5. - Concluded.

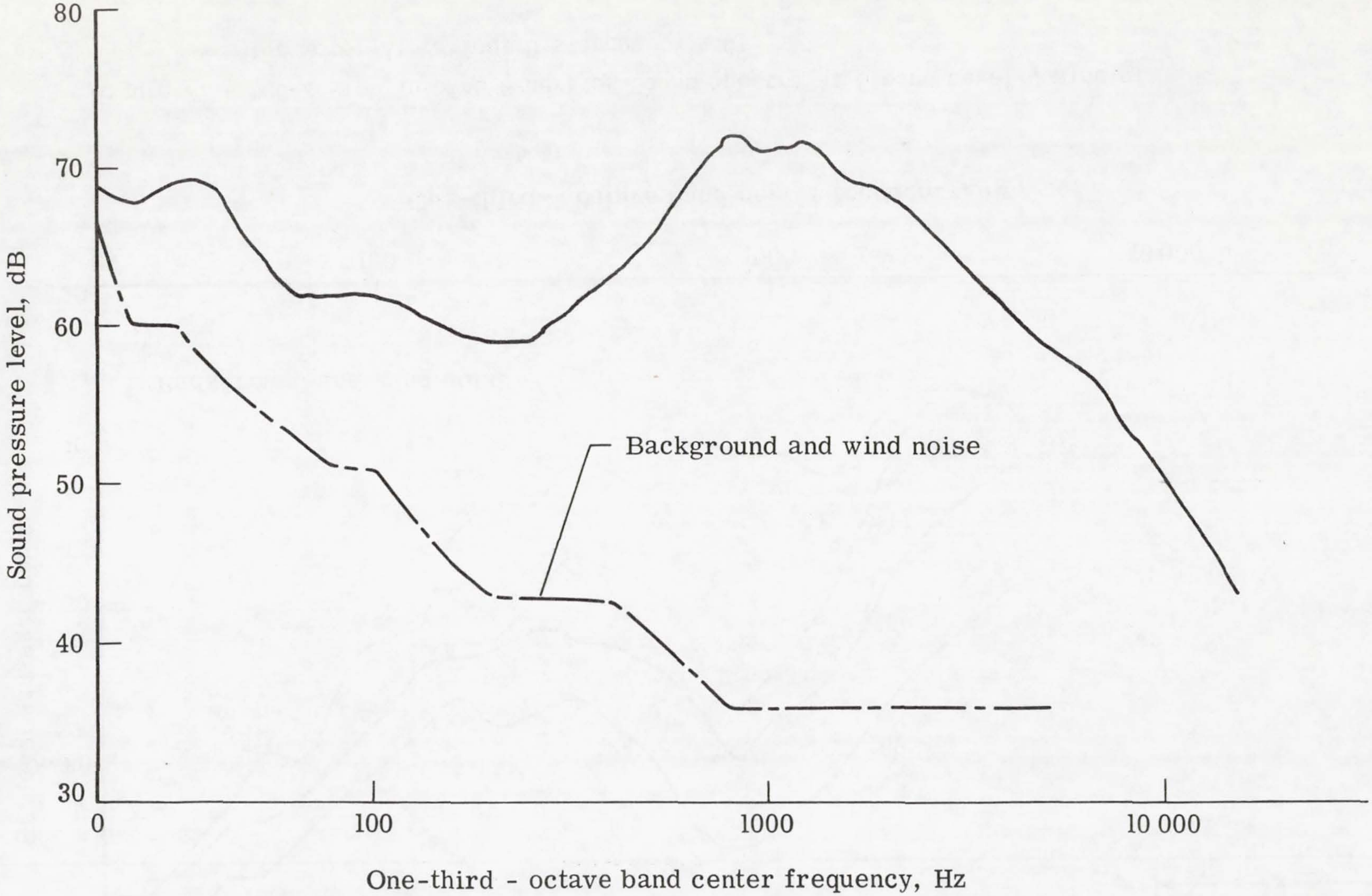


Figure 6. - Near Field Sound Spectrum of MOD-2 Wind Turbine Generator.
$X = 23$ M $\alpha = 90^{0}$.

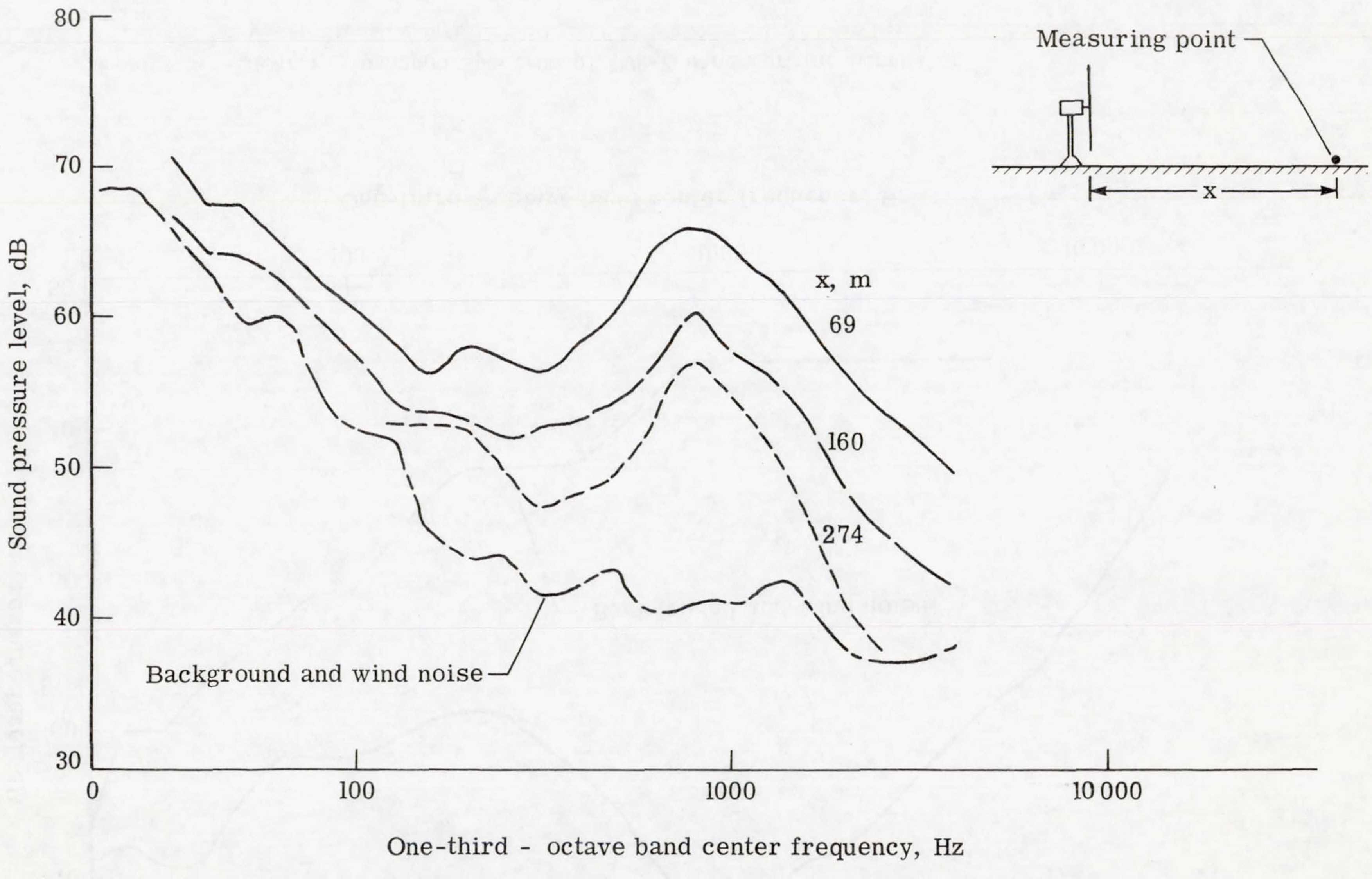
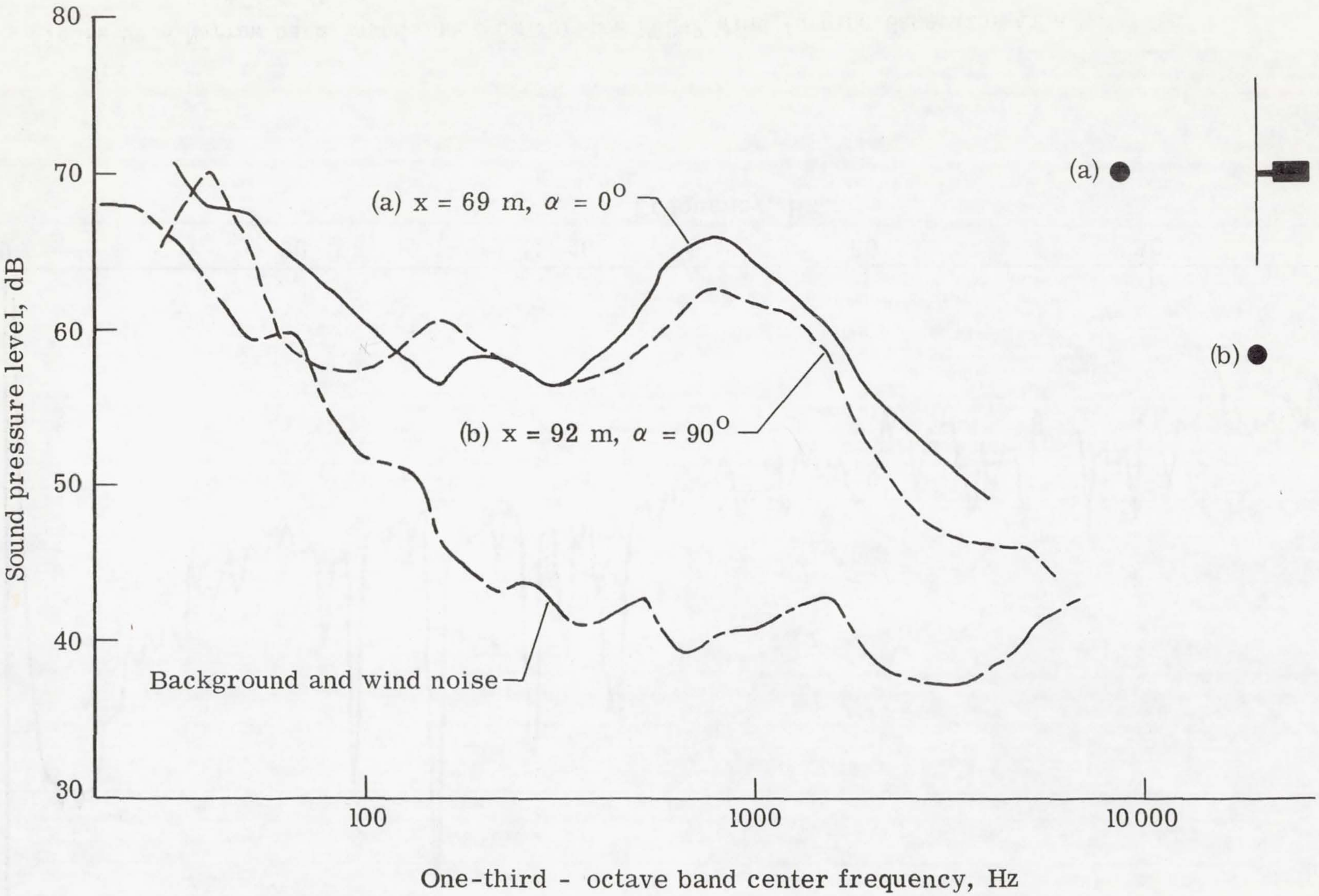


Figure 7. - MOD-2 Wind Turbine Generator Sound Spectra At Ground Level Upwind of The Rotor At Various Distances, $\alpha = 0^{o}$.



RPM = 17.5

2 BLADES
CHORD: 4.3 TO 1.43 m (2.148)
SPAN: 45.7 m
RPM: 17.5

Figure 8. - Comparison of MOD-2 Wind Turbine Generator Sound Spectra for Two Different Measurement Points.

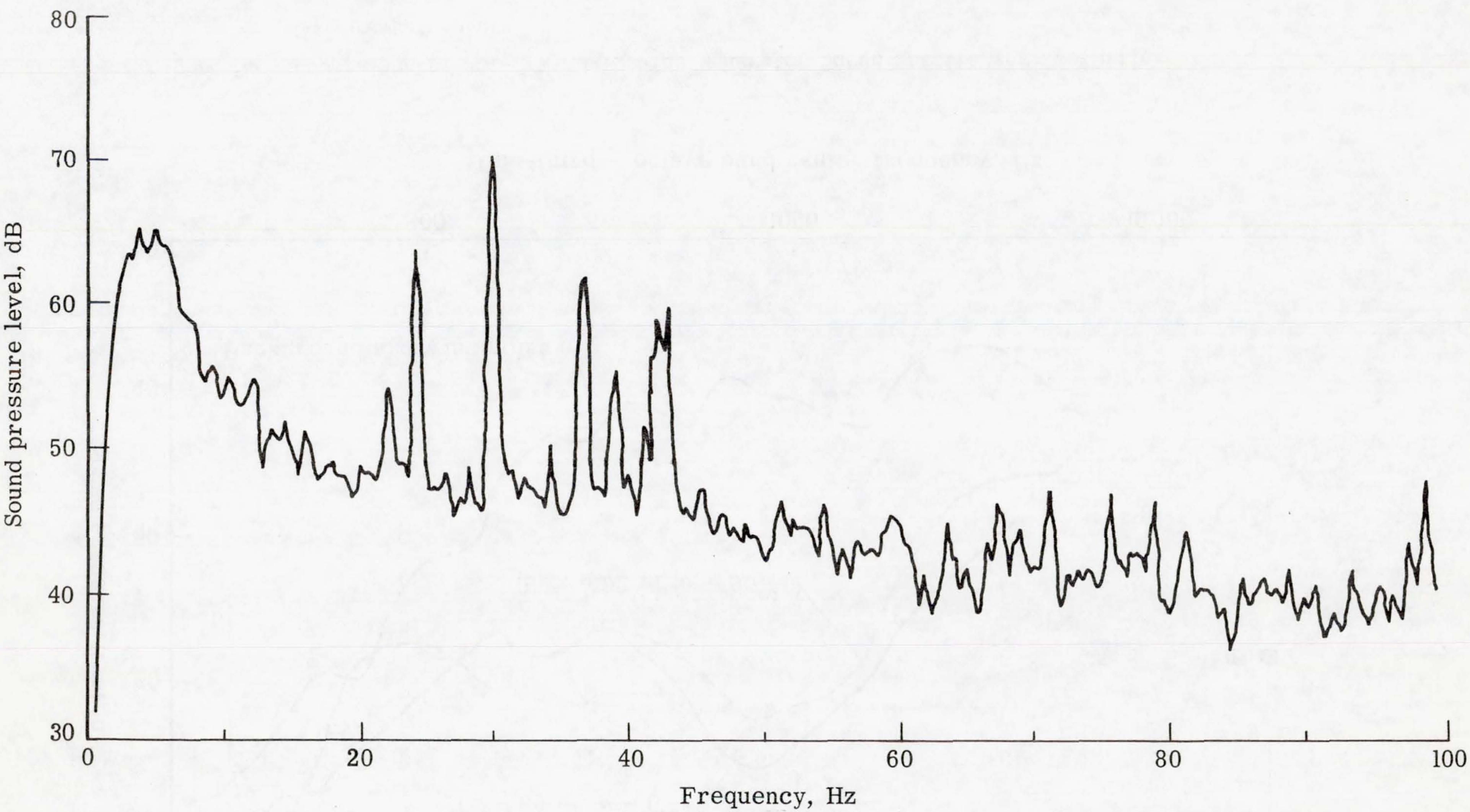


Figure 9. - Narrow Band Sound Spectrum for the MOD-2 Wind Turbine Generator at a Distance of 92 m in the Plane of Rotation. Effective Band Width = 0.25 Hz.

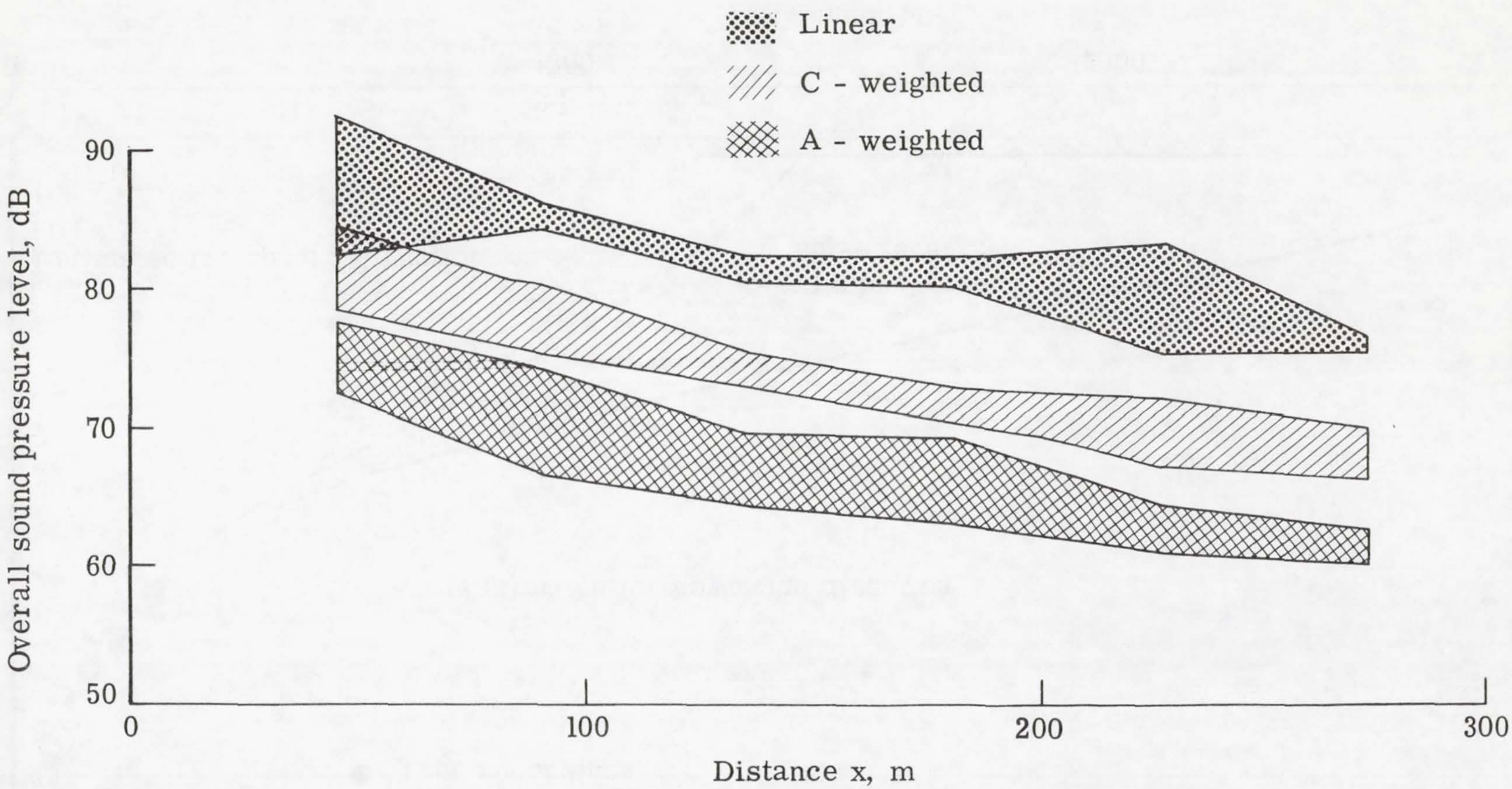


Figure 10. - Ranges of Measured Overall Sound Pressure Levels for the MOD-2 Wind Turbine Generator for a Range of Azimuth Angles from 0^{o} to 180^{o} for Three Different Weighting Scales.

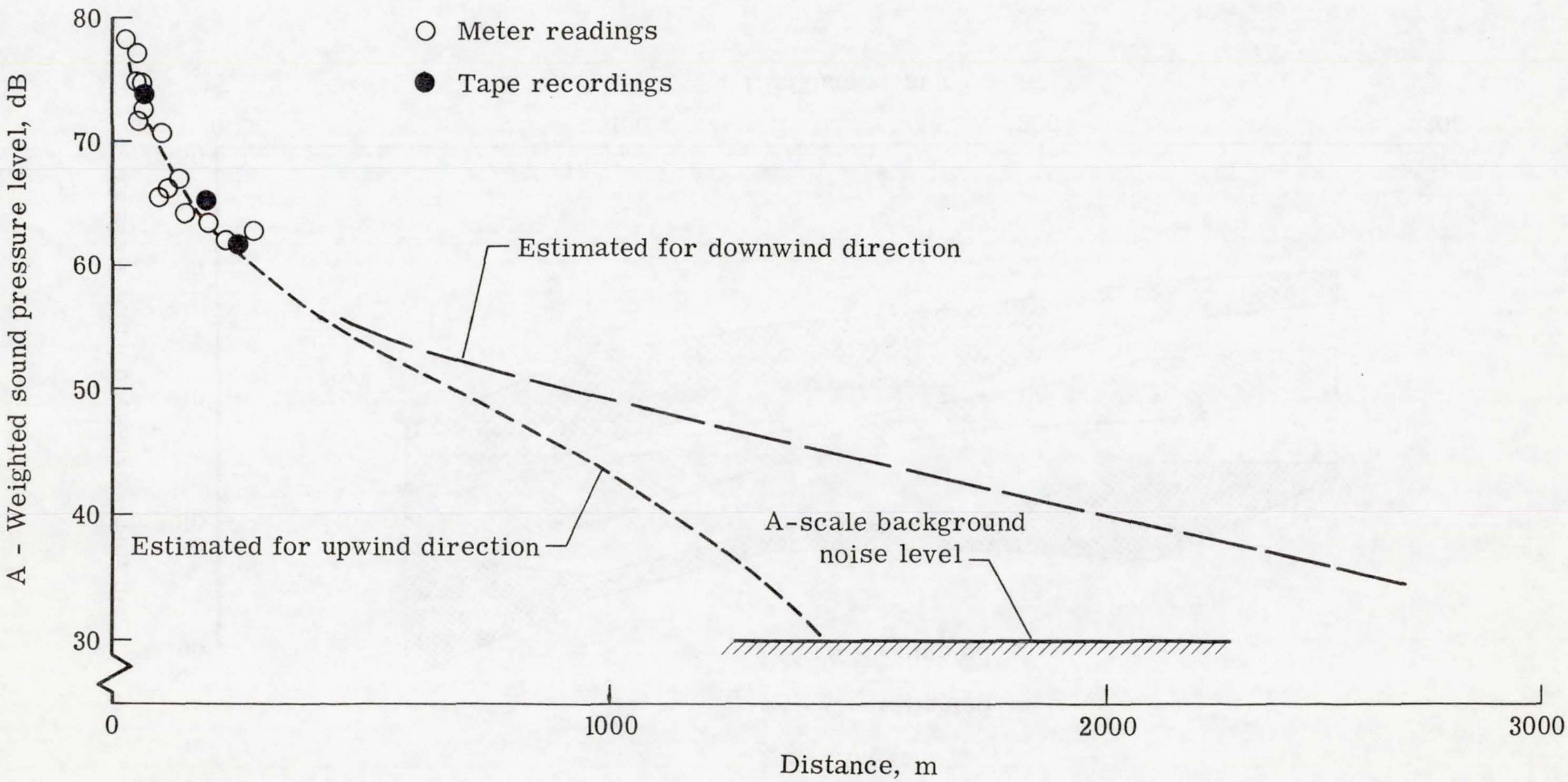


Figure 11. - A-Scale Overall Sound Pressure Levels as a Function of Distance for the MOD-2 Wind Turbine Generator for Wind Velocities of 7.6 to 13.4 m/sec.

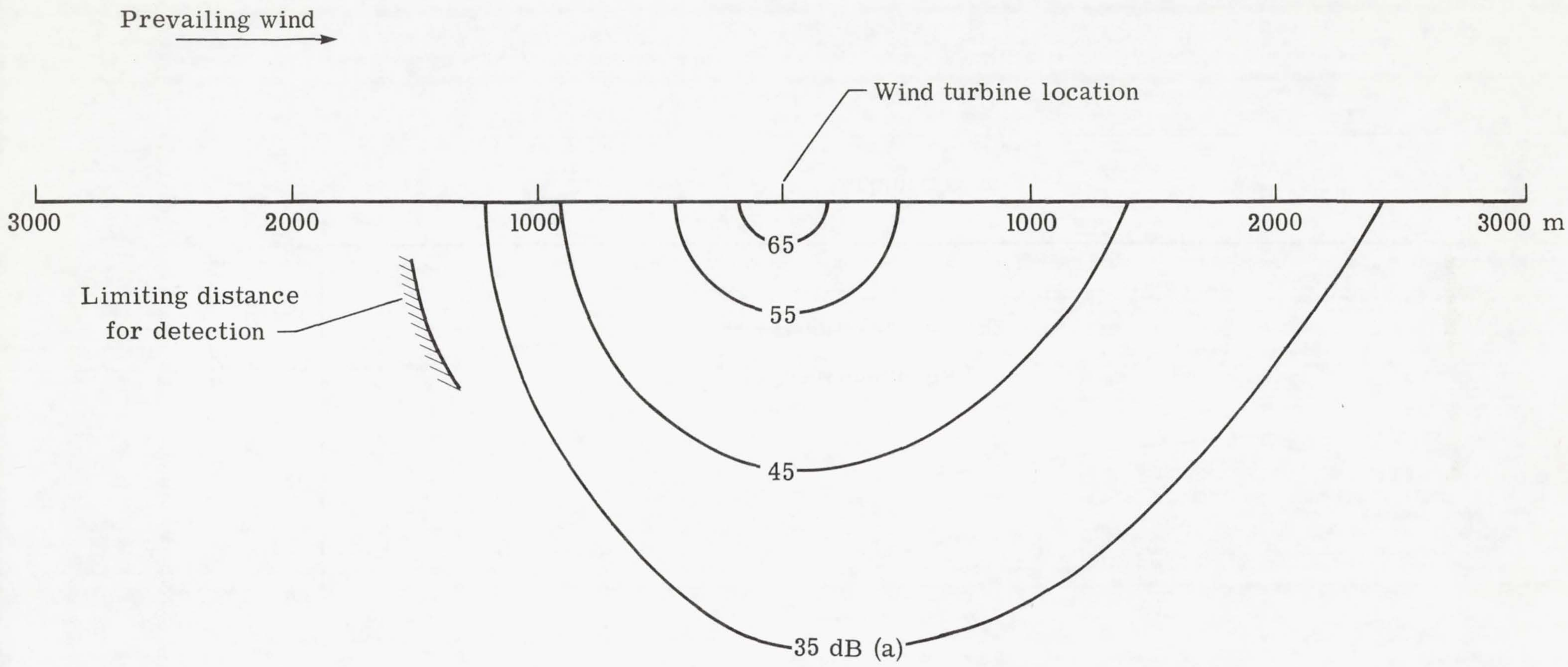


Figure 12. - Estimated A-Scale Overall Noise Level Contours for the MOD-2 Wind Turbine Generator, for Wind Velocities of 7.6 to 13.4 m/sec.

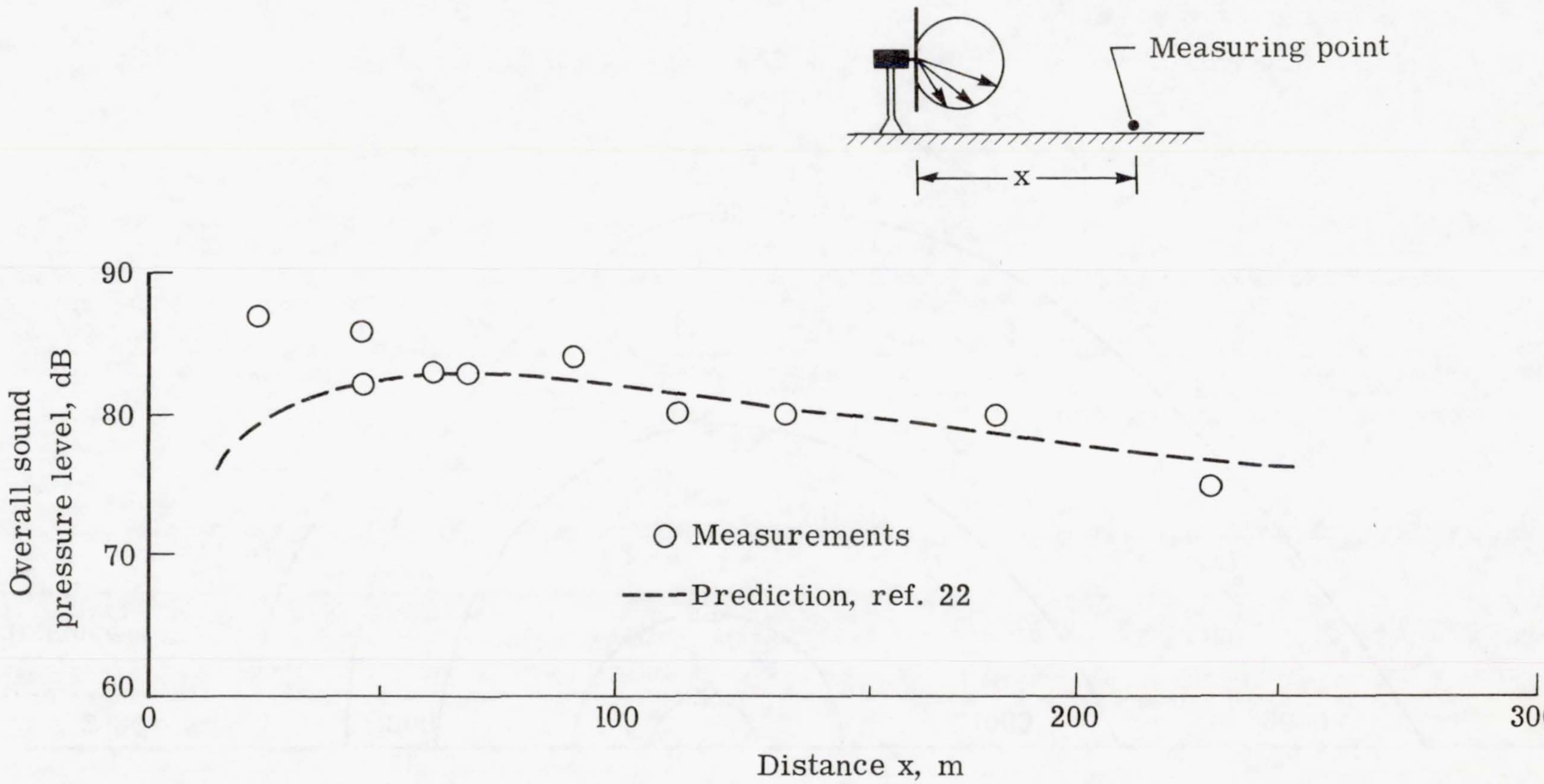


Figure 13.. - Comparison of Measured Overall Sound Pressure Levels for the MOD-2 Wind Turbine Generator with Predicted Values by the Method of Ref. 22.

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15. Supplementary Notes

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16. Abstract

Sound measurements have been made for the MOD-2 wind turbine generator for wind conditions of 7.6 to 13.4 m/sec and for output power ratings of about 1-2 MW. Both broad band and narrow band data were obtained for a range of distances and azimuth angles from the machine.

The rotor sound spectra are random in character and peak in the frequency ranges 30-50 Hz and 800-1300 Hz. Both peaks are predictable from experience with helicopter rotors and propellers. Results suggest that the lower frequency peak is due to the effects of inflow turbulence and the higher frequency peak is due to the interactions of the turbulent boundary layers with the trailing edges of the blades. The boundary layer related sound is the dominant component in the audible frequency range and determines the detectability of the machine. It could be detected at a distance of 1350 m in the upwind direction where the background noise was 30 dB (A) and at distances in excess of 2100 m in the downwind direction. Discrete frequency sound components associated with the power generation equipment are measurable in the direction normal to the axis of rotation but are not believed to be significant for detection or community response.

17. Key Words (Suggested by Author(s))	18. Distribution Statement
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